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Highlights from Five Years at the B Factories

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The highlights and conflicts at the B Factories are briefly reviewed. CP violation was established in 2001 in $B^0 \rightarrow J/\psi K_S$ and related modes, which has now become a precision measurement of CP violation in B^0 - \bar{B}^0 mixing. However, the situation for the $B^0 \rightarrow \pi^+\pi^-$ and charmless $b \rightarrow s$ modes, which probe also CP violation in the *decay* amplitude, are not quite settled yet. They could be hinting at presence of both strong (CP conserving) and new physics (CP violating) phases. We critically assess the developments and discuss some related discrepancies and highlights, such as observation of direct CP violation, and make a projection towards the next few years.

Keywords: CP violation; B mesons; strong phase; new physics.

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1. Introduction

CP violation (CPV) was discovered¹ in K^0 - \bar{K}^0 mixing in 1964. With it we came to realize, in terms of the Sakharov conditions,² that CPV is a prerequisite for understanding the baryon asymmetry of our Universe. However, it took another 35 years, until the measurement³ of ε'_K , or “direct” CPV (DCPV), for us to put the superweak⁴ (CPV in K^0 mixing only, but not in K decay) model to rest. Thus was the paucity of CPV in the last century.

The 21st century began with a roaring start in observations of CPV in the B meson system. Indirect CPV, or CPV in B^0 - \bar{B}^0 mixing, was firmly established^{5,6} in 2001. By 2004, DCPV was established^{7,8} in $B^0 \rightarrow K^+\pi^-$ decay. The history of the kaon system was repeated, in not quite the same way, in just 3 years. The B system also opens up a host of CPV and other observables.

The precursor to the modern view of CPV came a year before 1964, with the Cabibbo angle ($\sin \theta_C$) proposal⁹ that unified strange and nonstrange weak decays. By 1970, the GIM mechanism called for two generations of quarks and leptons, making $\sin \theta_C$ a genuine rotation angle of a 2×2 matrix. The two generation picture was completed with the J/ψ discovery of November 1974. But in 1973, Kobayashi and Maskawa (KM) realized¹⁰ that, upon generalizing quark mixing to 3 generations,

2 *W.S. Hou*

i.e. from 2×2 to 3×3 matrix, one has a *unique* CPV phase. Together with the establishment of the gauge theory of strong and electroweak interactions, by the mid-1970's the CKM quark mixing picture became an integral part of the Standard Model (SM), which has withstood test upon test for the past 30 years.

The ε'_K parameter suffers from hadronic uncertainties that make the extraction of fundamental parameters difficult. In 1979 it was realized¹¹ that the B system offers much better prospects. In the so-called mixing-decay CPV mechanism in $B^0 \rightarrow J/\psi K_S$, not only one expects the effect to be large, but because the decay amplitude is free from CPV phases, one can make a clean measure of the CPV phase $\sin 2\phi_1$ (also called $\sin 2\beta$) in the CKM “unitarity triangle”.

Several developments were pivotal to the realization of such measurements. In 1983, the B hadron lifetime was found to be much prolonged,¹² and $b \rightarrow c$ transitions dominated over $b \rightarrow u$ transitions. This stimulated the application of silicon based vertex detectors, while we now know that, taking $V_{us} \equiv \lambda \simeq 0.22$ as real, we have

$$V_{cb} = A\lambda^2, \quad V_{ub} = A\lambda^3(\rho - i\eta), \quad (1)$$

with $A \simeq 0.8$ and $\sqrt{\rho^2 + \eta^2} \sim 0.3\text{--}0.4$. It is remarkable that the progressive smallness of off-diagonal CKM matrix elements explains why CPV effect is so small in SM, as one needs the participation of all 3 generations. Second, in 1987 the ARGUS experiment discovered¹³ large $B^0\text{--}\bar{B}^0$ oscillations, i.e. $\Delta m_{B_d} \simeq 0.5\Gamma_B$. This was not only the harbinger for the heaviness of the top quark, it provided an almost ideal setting for the mixing-decay CPV mechanism to be realized. Finally, as the CLEO experiment was making upgrades, and when discussions were ongoing at PSI for a new B facility, Oddone suggested in 1988 to make the e^- and e^+ beams *asymmetric* in energy. The boosted B mesons made time-dependent measurements possible. Serious studies soon followed at KEK and SLAC, and by 1994 both places embarked on the construction of asymmetric e^+e^- “B factories”, the very successful KEKB and PEP-II colliders, as well as the Belle and BaBar detectors. After commissioning in 1999, by 2004 each experiment had accumulated more than 200M $B\bar{B}$ events, more than a factor of 20 over what CLEO collected throughout the 1990's.

The aim of this brief review is to give an account of the competitive history, the major milestones, as well as the ongoing debates if not controversies.

2. Raison D’Etre: $B^0 \rightarrow J/\psi K_S$ and $\sin 2\phi_1/\sin 2\beta$ Measurement

The physics of CPV in mixing-decay interference is rather close to the classic double slit experiment. Consider a CP eigenstate f that both \bar{B}^0 and B^0 can decay to. Besides the $\bar{B}^0 \rightarrow f$ decay amplitude, an initial \bar{B}^0 meson can oscillate into a B^0 meson and then decay to f . The interference pattern is measured to determine CPV in both the mixing and decay amplitudes. We note that CPV is measurable only when the two interfering amplitudes, A_1 and A_2 , have both CP violating as well as

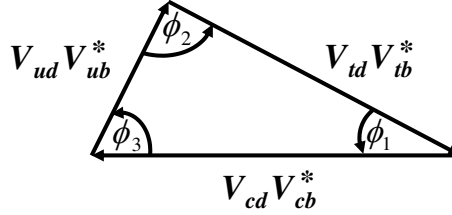


Fig. 1. The unitarity triangle, Eq. (4), probed by the B factories.

CP conserving relative phase differences. That is,

$$A_{CP} = \frac{2|A_1||A_2| \sin(\theta_1 - \theta_2) \sin(\delta_1 - \delta_2)}{|A_1|^2 + |A_2|^2 + 2|A_1||A_2| \cos(\theta_1 - \theta_2) \cos(\delta_1 - \delta_2)}, \quad (2)$$

which vanishes if either the CP violating or CP conserving phase differences $\theta_1 - \theta_2$, $\delta_1 - \delta_2$ vanish. Here, the oscillation phase $e^{-i\Delta m t}$ provides the latter.

For the “golden mode” of $f = J/\psi K_S$, the $\bar{B}^0 \rightarrow J/\psi K_S$ decay is dominated by the tree level $b \rightarrow c\bar{c}s$ hence $\propto V_{cb}V_{cs}^*$ in amplitude. Thus, to a very good approximation, the decay amplitude is real, and the mixing-decay mechanism measures the CPV phase in the $\bar{B}^0 \rightarrow B^0$ mixing amplitude, which is $\propto V_{td}^{*2}$ in SM.

The CKM quark mixing matrix V governs the strength of $d_j \rightarrow u_i$ weak transitions. With Eq. (1), it can be put in the form

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}, \quad (3)$$

to order $\mathcal{O}(\lambda^4)$. The matrix V is unitary, and the relation we probe is

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0, \quad (4)$$

which is visualized as the unitarity triangle (UT) shown in Fig. 1. It is remarkable that the fundamental phenomena of CPV can have such simple geometric representation. The CPV phase of V_{td}^{*2} probed by $\bar{B}^0/B^0 \rightarrow J/\psi K_S$ is $\sin 2\phi_1$ (or $\sin 2\beta$).

2.1. Master Formula and Template for TCPV Measurement

At B factories, the time-dependent CPV (TCPV) asymmetry for $B \rightarrow f$ decay is

$$\begin{aligned} A(\Delta t) &\equiv \frac{\Gamma(\bar{B}^0(\Delta t) \rightarrow f) - \Gamma(B^0(\Delta t) \rightarrow f)}{\Gamma(\bar{B}^0(\Delta t) \rightarrow f) + \Gamma(B^0(\Delta t) \rightarrow f)} \\ &= -\xi_f(\mathcal{S}_f \sin \Delta m \Delta t + \mathcal{A}_f \cos \Delta m \Delta t), \end{aligned} \quad (5)$$

where $\Delta m \equiv \Delta m_{B_d}$, ξ_f is the CP eigenvalue of f , $B^0(\Delta t)$ denotes the state at time Δt starting from B^0 at $\Delta t = 0$, and (BaBar uses $\mathcal{C}_f \equiv -\mathcal{A}_f$)

$$\mathcal{S}_f = \frac{2 \operatorname{Im} \lambda_f}{|\lambda_f|^2 + 1}, \quad \mathcal{A}_f = \frac{|\lambda_f|^2 - 1}{|\lambda_f|^2 + 1}, \quad (6)$$

4 *W.S. Hou*

where \mathcal{A}_f measures DCPV, and λ_f is defined as

$$\lambda_f = \frac{q \langle f | S | \overline{B}^0 \rangle}{p \langle f | S | B^0 \rangle}, \quad (7)$$

which depends on both B^0 mixing, i.e. $B_{H,L} = p B^0 \mp q \overline{B}^0$, and decay to state f . The lifetime difference between the two neutral B mesons have been ignored (a very good approximation for B_d), so $q/p \cong e^{-2i\phi_1}$ (so $|q/p| \cong 1$). For the golden $J/\psi K_S$ mode, the decay amplitude is real in the standard phase convention, hence

$$\mathcal{S}_{J/\psi K_S} \cong \sin 2\phi_1, \quad \mathcal{A}_{J/\psi K_S} \cong 0, \quad (8)$$

to very good accuracy. Many other $b \rightarrow s(c\bar{c})_{\text{charmonium}}$ modes are also collected and, correcting for ξ_f , adds to the statistics.

The $J/\psi K_S$ events are collected by detecting $J/\psi \rightarrow \ell^+ \ell^-$ ($\ell = e, \mu$) and $K_S \rightarrow \pi^+ \pi^-$ (and $\pi^0 \pi^0$). Two CMS variables that utilize the special kinematics of $\Upsilon(4S) \rightarrow B\overline{B}$ decay greatly enhances signal over background events. One is the beam-constrained mass $M_{bc} = \sqrt{(E_{\text{CM}}/2) - \vec{p}_{\text{meas}}^2}$, and the other is the energy difference $\Delta E = E_{\text{meas}} - E_{\text{CM}}/2$, where \vec{p}_{meas} and E_{meas} are the measured momentum and energy in CMS. Knowing that $\Upsilon(4S) \rightarrow B\overline{B}$ only, and substituting the much better known CMS beam energy $E_{\text{CM}}/2$ for E_B greatly improves resolution.

Two special requirements in Eq. (5) make construction of the B factories necessary. Since the $J/\psi K_S$ final state cannot tell between B^0 or \overline{B}^0 decay, we need to “tag” its flavor. At B factories one utilizes the quantum phenomenon that, after $\Upsilon(4S)$ decay, the $B\overline{B}$ system remains coherent until one of the B mesons decays. Assuming that this “tagging” side is a B decay at t_{tag} , then the other side evolves as a \overline{B}^0 meson until it decays to the CP eigenmode $J/\psi K_S$ at time t_{CP} . Thus, $\Delta t \equiv t_{CP} - t_{\text{tag}}$ in Eq. (5). Note that Δt can be of either sign.

Since B momentum in $\Upsilon(4S)$ frame is very small, to observe the decay points of the two B mesons, one boosts the $\Upsilon(4S)$ frame at an asymmetric B factory. To a very good approximation $\Delta t \simeq \Delta z / \beta \gamma c$, where β is the boost of $\Upsilon(4S)$ in lab frame, and $\beta \gamma = 0.56$ and 0.425 , respectively, for PEP-II and KEKB. One also needs a vertex detector (SVT at BaBar and SVD at Belle) of sufficient accuracy.

For flavor tagging, one utilizes primary $b \rightarrow \ell^- X$ and secondary $b \rightarrow c \rightarrow \ell^+$ leptons, secondary K^\pm and Λ 's from $b \rightarrow c \rightarrow s$ sequence, low energy π^\pm from $D^{*\pm}$, and high energy tracks such as π 's from $B \rightarrow \overline{D}\pi$. The results are combined into a multidimensional likelihood function to determine a tag-side charge $q = \pm$. Reconstructed self-tagged modes (such as $D^{*-} \ell^+ \nu$, $D^{(*)-} \pi^+$, $D^{*-} \rho^+$ etc.) from actual data are used to measure the wrong-tag fraction w_i (leading to a dilution factor of $1 - 2w_i$ in Eq. (5)) for each tagging or purity category i . The total effective tagging efficiency is around 0.27–0.28.

One final technicality is “blind” analysis. Since the CP asymmetry $A(t)$ can be of either sign, the analysis is performed “blind” to avoid bias. That is, the value of $\sin 2\phi_1$ (and the CP asymmetry in the Δt distribution) from the fit remains hidden

until the analysis is completed. The statistical error is largely unaffected, but all systematic uncertainties can be studied without knowing the value of $\sin 2\phi_1$.

2.2. Measurements

After approval in 1993 and 1994, respectively, both the SLAC and KEK B factories were commissioned successfully and reported engineering results in 1999. Based on 9 and 6.2 fb⁻¹ of data, respectively, the first measurements for $\sin 2\beta$ and $\sin 2\phi_1$ were reported at the ICHEP 2000 meeting in Osaka,¹⁴

$$\begin{aligned}\sin 2\beta &= 0.12 \pm 0.37 \pm 0.09, & (\text{BaBar, } 9 \text{ fb}^{-1}) \\ \sin 2\phi_1 &= 0.45^{+0.43+0.07}_{-0.44-0.09}, & (\text{Belle, } 6.2 \text{ fb}^{-1})\end{aligned}\quad (9)$$

which, being consistent with zero, gave physicists the impression that $\sin 2\beta$ might deviate¹⁵ from SM expectations! This continued to be the case, especially for BaBar, with the first published results,¹⁶

$$\sin 2\phi_1 = 0.58^{+0.32+0.09}_{-0.34-0.10}, \quad (\text{Belle, } 10.5 \text{ fb}^{-1}) \quad (10)$$

$$\sin 2\beta = 0.34 \pm 0.20 \pm 0.05, \quad (\text{BaBar, } 20.7 \text{ fb}^{-1}) \quad (11)$$

Compared to the summer 2004 average of¹⁷

$$\sin 2\beta / \sin 2\phi_1 = 0.726 \pm 0.037, \quad (\text{HFAG Summer 2004}) \quad (12)$$

(B factory average is 0.725) BaBar's result is low by 2σ . Just before Lepton-Photon 2001, however, BaBar reported⁵

$$\sin 2\beta = 0.59 \pm 0.14 \pm 0.05. \quad (\text{BaBar, } 32\text{M } B\bar{B}) \quad (13)$$

Only 9M $B\bar{B}$ events were added, but with significant improvement in SVT alignment. Also, analysis method was improved. When applied to previous data of 23M $B\bar{B}$ events, the result was 0.32 ± 0.18 . But for the 2001 data of 9M, the result was 0.83 ± 0.23 , which deviated by 1.8σ from 1999-2000 result. On the other hand, Belle reported at LP01 the stunning result of⁶

$$\sin 2\phi_1 = 0.99 \pm 0.14 \pm 0.06. \quad (\text{Belle, } 31.3\text{M } B\bar{B}) \quad (14)$$

Although at some variance, the combined result of 0.79 not only established CPV in B system beyond doubt. It is also quite consistent with the 2004 HFAG average, showing the power of having two B factories. Both Belle and BaBar published details of their 2001 analysis, while another round of analyses in 2002 gave

$$\begin{aligned}\sin 2\beta &= 0.741 \pm 0.067 \pm 0.034, & (\text{BaBar, } 88\text{M}) \\ \sin 2\phi_1 &= 0.719 \pm 0.074 \pm 0.035, & (\text{Belle, } 85\text{M})\end{aligned}\quad (15)$$

which are in rather good agreement. The case is fully settled. We plot the measurements of Eqs. (9)–(15) in Fig. 2.

Direct CP asymmetry $\mathcal{A}_{J/\psi K_S}$ has also been searched for and is found to be consistent with zero, confirming the expectation in Eq. (8). Polarization and triple

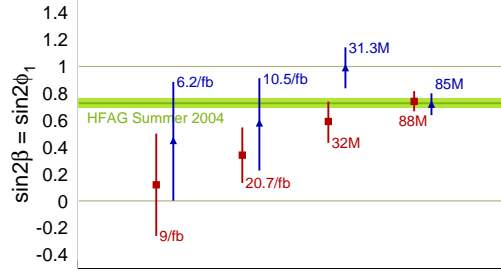


Fig. 2. Measurements of $\sin 2\phi_1 / \sin 2\beta$ at the B factories. Square (triangle) is for BaBar (Belle).

product correlations have also been studied in $B \rightarrow J/\psi K^*$ decays, where 3 partial waves are present. Although evidence is found for final state interactions, no indication was found for deviations from SM. The current average $\sin 2\phi_1$ value of Eq. (12) is in good agreement with a global fit¹⁸ to ϵ_K , Δm_{B_d} , $|V_{ub}/V_{cb}|$ data and limit on B_s mixing. Up to a four fold ambiguity, the preferred value for ϕ_1 in Fig. 1 is $23.3^\circ \pm 1.6^\circ$.

The *raison d'être* of the B factories was already completed within two years of turning on, and $\sin 2\phi_1$ is now a precision measurement. No indication is found for deviation from the KM picture of CPV.

3. $B^0 \rightarrow \pi^+\pi^-$ and ϕ_2/α Measurement

In early times, it was thought that $\overline{B}^0 \rightarrow \pi^+\pi^-$ decay would proceed by the $b \rightarrow u\bar{u}d$ tree diagram, hence the decay amplitude ratio $\langle \pi^+\pi^- | S | \overline{B}^0 \rangle / \langle \pi^+\pi^- | S | B^0 \rangle = V_{ub}/V_{ub}^* = e^{-2i\phi_3}$ (or $e^{-2i\gamma}$), so $\lambda_{\pi^+\pi^-} = e^{-2i\phi_1} e^{-2i\phi_3} = e^{-2i(\pi-\phi_2)} = e^{+2i\phi_2}$. One could thus measure $\sin 2\phi_2$ via the $\pi^+\pi^-$ mode. If $b \rightarrow u\bar{u}d$ tree dominance were true, one would also expect $\mathcal{A}_{\pi^+\pi^-}$ to vanish.

This picture was already shattered by the CLEO observation¹⁹ of $K^-\pi^+$ before $\pi^-\pi^+$. The $b \rightarrow u\bar{u}s$ tree process should be suppressed by $|V_{us}/V_{ud}|^2 \sim 1/20$ in rate w.r.t. the $b \rightarrow u\bar{u}d$ tree process. The CLEO observation clearly demonstrates that the loop-induced “penguin” $b \rightarrow s\bar{q}q$ process dominates $\overline{B}^0 \rightarrow K^-\pi^+$. With a $K^-\pi^+$ rate 4 times that of $\pi^+\pi^-$ mode, we now expect the penguin amplitude to be of order 30% of the tree for $\overline{B}^0 \rightarrow \pi^+\pi^-$ decay. The penguin amplitude not only brings in weak phases, it could introduce strong phases relative to the tree amplitude as well. It is common practice to write²⁰

$$\lambda_{\pi^+\pi^-} = e^{+2i\phi_2} \frac{T + P e^{+i\phi_3} e^{i\delta}}{T + P e^{-i\phi_3} e^{i\delta}} = \frac{e^{+i\phi_2} - \hat{P} e^{-i\phi_1} e^{i\delta}}{e^{-i\phi_2} - \hat{P} e^{+i\phi_1} e^{i\delta}}, \quad (16)$$

where T and P are the magnitudes of the tree and penguin amplitudes, and δ is their strong phase difference. One can see that, if $\hat{P} \equiv P/T \rightarrow 0$, then $\lambda_{\pi^+\pi^-} \rightarrow e^{+2i\phi_2}$, but for $P/T \sim 0.3$, the extraction of ϕ_2 becomes rather complicated. The presence of P and δ also bring in hadronic uncertainties that are hard to deal with theoretically.

As there are more parameters than measurables, an isospin analysis²¹ involving $\pi^+\pi^0$ and $\pi^0\pi^0$ modes is necessary to fit for P/T and δ , in addition to ϕ_2 and ϕ_1 .

3.1. $\mathcal{S}_{\pi\pi}$, $\mathcal{A}_{\pi\pi}$ Measurements

As if theoretical difficulties were not enough, Belle and BaBar have not yet reached mutual agreement on their measurements of $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$.

The first measurement was reported by BaBar in 2001 based on 33M $B\bar{B}$ pairs,²²

$$\mathcal{S}_{\pi\pi} = +0.03^{+0.53}_{-0.56} \pm 0.11, \quad \mathcal{C}_{\pi\pi} = -0.25^{+0.45}_{-0.47} \pm 0.14, \quad (\text{BaBar, 33M}) \quad (17)$$

which is a null measurement serving the purpose of establishing technique. Then came the astonishing result²³ from Belle in 2002, based on $\sim 45\text{M}$ $B\bar{B}$ pairs,

$$\mathcal{S}_{\pi\pi} = -1.21^{+0.38+0.16}_{-0.27-0.13}, \quad \mathcal{A}_{\pi\pi} = +0.94^{+0.25}_{-0.31} \pm 0.09, \quad (\text{Belle, 45M}) \quad (18)$$

which is in strong contrast (note that $\mathcal{A}_f = -\mathcal{C}_f$; see Eq. (5)) with Eq. (17). Thus commenced the controversy between BaBar and Belle on $\mathcal{S}_{\pi\pi}$, $\mathcal{A}_{\pi\pi}$. We note that, although $\mathcal{S}_{\pi\pi}^2 + \mathcal{A}_{\pi\pi}^2 \leq 1$ according to Eq. (6), because of dilution (mistag) factors in the actual measurement of Eq. (5), it is possible for measured $\mathcal{S}_{\pi\pi}$, $\mathcal{A}_{\pi\pi}$ values to lie outside the “physical” region, especially if the CPV effect is large.

The next round came summer 2002 from BaBar with more than twice the data,²⁴

$$\mathcal{S}_{\pi\pi} = +0.02 \pm 0.34 \pm 0.05, \quad \mathcal{C}_{\pi\pi} = -0.30 \pm 0.25 \pm 0.04, \quad (\text{BaBar, 88M}) \quad (19)$$

which confirmed their earlier result. This was followed by Belle in early 2003,²⁵

$$\mathcal{S}_{\pi\pi} = -1.23 \pm 0.41^{+0.08}_{-0.07}, \quad \mathcal{A}_{\pi\pi} = +0.77 \pm 0.27 \pm 0.08, \quad (\text{Belle, 85M}) \quad (20)$$

which also confirmed their earlier result. The conflict continued.

At summer 2003 conferences, BaBar updated with the result²⁶

$$\mathcal{S}_{\pi\pi} = -0.40 \pm 0.22 \pm 0.03, \quad \mathcal{C}_{\pi\pi} = -0.19 \pm 0.19 \pm 0.05, \quad (\text{BaBar, 122M}) \quad (21)$$

which seems to move towards the Belle value. The reprocessing of old 88M $B\bar{B}$ pair data gave $\mathcal{S}_{\pi\pi} = -0.252 \pm 0.27$, $\mathcal{C}_{\pi\pi} = -0.166 \pm 0.22$, while the newly added 34M data gave $\mathcal{S}_{\pi\pi} = -0.67 \pm 0.35$, $\mathcal{C}_{\pi\pi} = -0.33 \pm 0.34$. This result went unpublished, probably because BaBar sought confirmation of the “move” with more data.

In early 2004, Belle announced²⁷ the observation of large CPV in $B^0 \rightarrow \pi^+\pi^-$,

$$\mathcal{S}_{\pi\pi} = -1.00 \pm 0.21 \pm 0.07, \quad \mathcal{A}_{\pi\pi} = +0.58 \pm 0.15 \pm 0.07, \quad (\text{Belle, 152M}) \quad (22)$$

claiming a 5.2σ effect w.r.t. $\mathcal{S}_{\pi\pi} = \mathcal{A}_{\pi\pi} = 0$, and 3.2σ evidence for DCPV ($\mathcal{A}_{\pi\pi} \neq 0$), regardless of $\mathcal{S}_{\pi\pi}$ value, indicating the presence of strong phases. Note that the value of $\mathcal{S}_{\pi\pi}^2 + \mathcal{A}_{\pi\pi}^2$ now does touch the “physical” boundary of 1.

BaBar updated with 227M $B\bar{B}$ pairs at summer 2004 conferences,²⁸

$$\mathcal{S}_{\pi\pi} = -0.30 \pm 0.17 \pm 0.03, \quad \mathcal{C}_{\pi\pi} = -0.09 \pm 0.15 \pm 0.04, \quad (\text{BaBar, 227M}) \quad (23)$$

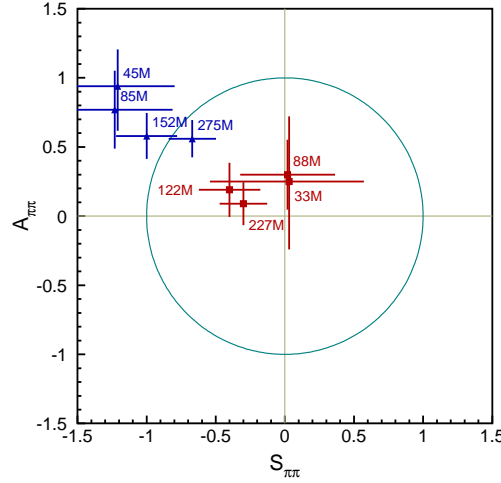


Fig. 3. Measurements of $S_{\pi\pi}$ and $A_{\pi\pi}$ ($= -C_{\pi\pi}$). Square (triangle) is for BaBar (Belle).

which, with almost doubling of summer 2003 data, moved slightly back. Belle has just updated²⁹ with full 2004 dataset of 275M $B\bar{B}$ pairs, giving

$$S_{\pi\pi} = -0.67 \pm 0.16 \pm 0.06, \quad A_{\pi\pi} = +0.56 \pm 0.12 \pm 0.06, \quad (\text{Belle, 275M}) \quad (24)$$

where $S_{\pi\pi}$ shifted downwards by more than 1σ , and now the central value satisfies $S_{\pi\pi}^2 + A_{\pi\pi}^2 \leq 1$. However, the conflict between Belle and BaBar remains at $\sim 2.3\sigma$. The results of Eqs. (17)–(24) are plotted in Fig. 3.

It is not clear whether the deviation between Belle and BaBar on $\pi^+\pi^-$ results is due to background, analysis method, or statistical fluctuation. The latest Belle analysis (275M) contains 2820 candidate events, corresponding to ~ 670 $\pi^+\pi^-$ signal events, and 250 $K^\pm\pi^\mp$, 1900 continuum ($e^+e^- \rightarrow q\bar{q}$ where $q = u, d, s, c$ quarks) background events in $M_{bc}-\Delta E$ signal window. The latest analysis (227M) of BaBar, making a multivariate, maximum likelihood and simultaneous fit for $\pi^+\pi^-$ and $K^\pm\pi^\mp$ (and K^+K^-), is less transparent: out of 68030 fitted events, ~ 470 $\pi^+\pi^-$ events are extracted, together with ~ 1600 $K^\pm\pi^\mp$ events. Compared to the $J/\psi K_S$ signal purity of over 97% and a larger effective rate, background is certainly much more significant in the $\pi\pi$ analysis. From Fig. 3, however, it is clear that there is some tendency of convergence between Belle and BaBar as more data is added. But combining the results may not yet be a good idea.

3.2. $\pi^0\pi^0$, $\rho\rho/\rho\rho$ Modes and the ϕ_2/α Program

To extract ϕ_2/α from $\pi\pi$ modes, an isospin analysis²¹ involving also the $\pi^+\pi^0$ and $\pi^0\pi^0$ modes is needed. The $\pi^+\pi^0$ rate is relatively well measured.¹⁷ With 124M $B\bar{B}$ pairs, BaBar found strong evidence³⁰ for the $\pi^0\pi^0$ mode with rate at $(2.1 \pm 0.6 \pm 0.3) \times 10^{-6}$, roughly half the $\pi^+\pi^-$ rate. This is much larger than

factorization expectations, but it is good for isospin analysis. Using 275M $B\bar{B}$ pairs, Belle observed³¹ the $\pi^0\pi^0$ mode at $(2.3^{+0.4+0.2}_{-0.5-0.3}) \times 10^{-6}$ with 5.8σ significance. However, with 227M $B\bar{B}$ pairs, the BaBar number went down to³² $(1.17 \pm 0.32 \pm 0.10) \times 10^{-6}$ with 5.0σ significance. A 2σ conflict exists, while the errors are still too large for performing the ϕ_2 program. And in any case, there is an 8-fold ambiguity for ϕ_2 determined this way. The path to ϕ_2 seems long and tortuous.

The $\rho\pi$ and $\rho\rho$ systems are the VP and VV counterparts of the $\pi\pi$ system, but clearly more complicated. The $\rho\pi$ system cannot be a CP eigenstate. In fact, $\bar{B}^0 \rightarrow \rho^-\pi^+$ and $\rho^+\pi^-$ are both possible. It has been suggested³³ that, together with $\bar{B}^0 \rightarrow \rho^0\pi^0$, a t -dependent Dalitz plot analysis of $B^0/\bar{B}^0 \rightarrow \pi^+\pi^-\pi^0$ can in principle determine α or ϕ_2 without discrete ambiguities, the latter resolved by the interference regions. Even with the simplifying assumption of $(\rho\pi)^0$ dominance of the Dalitz plot, this is a very difficult program. But BaBar has pursued it, finding³⁴ $\alpha = (113^{+27}_{-17} \pm 6)^\circ$. We caution, however, that Belle and BaBar do not yet agree on the strength of the $\rho^0\pi^0$ mode. Given the disagreement in $\pi\pi$ results, we prefer to wait for Belle to complete the Dalitz analysis. Belle has so far³⁵ only analyzed by treating $\rho^\pm\pi^\mp$ as quasi-two-body, giving results agreeing with BaBar in general. The combined¹⁷ result of $A_{\rho\pi}^{-+} = 0.47^{+0.13}_{-0.14}$ gives over 4σ evidence for DCPV in the $\bar{B}^0 \rightarrow \rho^-\pi^+$ (but not in $\bar{B}^0 \rightarrow \rho^+\pi^-$) mode, which echoes the $\pi\pi$ mode. There seems to be strong phase difference between tree and penguin amplitudes.

The VV modes have 3 helicity amplitudes. BaBar has found the $B^0 \rightarrow \rho^+\rho^-$ mode to be predominantly longitudinal, hence is largely a CP eigenstate. They also find, unlike the $\pi\pi$ and $\rho\pi$ situation, a very small $\rho^0\rho^0$. BaBar has therefore pursued the analysis vigorously. Their current measurements of $\mathcal{S}_{\rho\rho}$ and $\mathcal{A}_{\rho\rho}$ are consistent with zero. Using isospin relations and their results for $\rho^+\rho^0$ and $\rho^0\rho^0$ modes, BaBar gives³⁶ $\alpha = (96 \pm 10 \pm 4 \pm 11)^\circ$, where the last error is due to penguin uncertainties. Belle, however, has yet to give their results. Given that the $\rho\rho$ analysis is more complicated than the $\pi\pi$ case, and BaBar and Belle are in dispute on the latter, we feel it is premature to conclude. We note, however, that $\alpha \sim 100^\circ$ is in good agreement with the “CKM fit”¹⁸ result not utilizing CPV B measurements.

4. Penguin Dominant $b \rightarrow s$ Modes and New Physics

As we have seen, penguin $b \rightarrow s\bar{q}q$ processes dominate over the tree $b \rightarrow u\bar{u}s$ process, enhancing e.g. the $\bar{B}^0 \rightarrow K^-\pi^+$ mode over the $\pi^-\pi^+$ mode by a factor of 4 in rate. The $b \rightarrow s$ penguins are induced by virtual loops involving $u\bar{u}$, $c\bar{c}$ and $t\bar{t}$ quarks, which are governed by the UT relation

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0. \quad (25)$$

Unlike the UT relation of Eq. (4) for $b \rightarrow d$ transitions, where all three terms are on equal footing, the first term in Eq. (25), $|V_{us}V_{ub}^*| \cong A\lambda^4\sqrt{\rho^2 + \eta^2}$, is much smaller than the other two terms $|V_{cs}V_{cb}^*| \cong |V_{ts}V_{tb}^*| \cong A\lambda^2$. One has a rather collapsed UT compared to Fig. 1, and $V_{cs}V_{cb}^*$, $V_{ts}V_{tb}^*$ are real to $\mathcal{O}(\lambda^4)$. This implies that

10 *W.S. Hou*

the decay amplitude is basically real for penguin dominant modes. Thus, TCPV measurements in $b \rightarrow s$ penguin dominant CP eigenstates should give $\sin 2\phi_1$, just like the $b \rightarrow s(\bar{c}c)_{\text{charmonium}}$ modes. This constitutes a test of SM, and at the same time, any deviation could indicate the presence of New Physics (NP). In the past several years, the $B^0 \rightarrow \phi K_S$ and $\eta' K_S$ modes have caused some sensation.

4.1. Measurements in $B^0 \rightarrow \phi K_S$ and $\eta' K_S$

The principles for TCPV study is the same as $J/\psi K_S$ and $\pi^+\pi^-$ modes. The first measurement of a penguin dominant $b \rightarrow s$ mode was performed by Belle for $B^0 \rightarrow \eta' K_S$ in 2002 with 45M $B\bar{B}$ pairs, giving³⁷

$$\mathcal{S}_{\eta' K_S} = +0.28 \pm 0.55^{+0.07}_{-0.08}, \quad \mathcal{A}_{\eta' K_S} = +0.13 \pm 0.32^{+0.09}_{-0.06}, \quad (\text{Belle, 45M}) \quad (26)$$

using $\eta' \rightarrow \eta\pi^+\pi^-$ ($\eta \rightarrow \gamma\gamma$) and $\rho^0\gamma$. This result is consistent with zero, but was soon updated at ICHEP 2002, together with ϕK_S , to³⁸

$$\mathcal{S}_{\eta' K_S} = +0.71 \pm 0.37^{+0.05}_{-0.06}, \quad \mathcal{A}_{\eta' K_S} = +0.26 \pm 0.22 \pm 0.03, \quad (\text{Belle, 85M}) \quad (27)$$

$$\mathcal{S}_{\phi K_S} = -0.73 \pm 0.64 \pm 0.22, \quad \mathcal{A}_{\phi K_S} = -0.56 \pm 0.41 \pm 0.16, \quad (\text{Belle, 85M}) \quad (28)$$

where $\mathcal{S}_{\eta' K_S}$ became consistent with $\mathcal{S}_{J/\psi K_S}$, but $\mathcal{S}_{\phi K_S}$ has the opposite sign! This caused a sensation since BaBar also reported³⁹ a negative number,

$$\mathcal{S}_{\phi K_S} = -0.19^{+0.52}_{-0.50} \pm 0.09, \quad (\text{BaBar, 88M}) \quad (29)$$

which went unpublished. However, BaBar published the result for $\eta' K_S$,⁴⁰

$$\mathcal{S}_{\eta' K_S} = +0.02 \pm 0.34 \pm 0.03, \quad \mathcal{C}_{\eta' K_S} = +0.10 \pm 0.22 \pm 0.04, \quad (\text{BaBar, 89M}) \quad (30)$$

(again, $\mathcal{C} = -\mathcal{A}$) which seems more consistent with Eq. (26) than Eq. (27).

Summer 2003 was rather exciting. Belle updated with 152M, giving⁴¹

$$\mathcal{S}_{\eta' K_S} = +0.43 \pm 0.27 \pm 0.05, \quad \mathcal{A}_{\eta' K_S} = -0.01 \pm 0.16 \pm 0.04, \quad (\text{Belle, 152M}) \quad (31)$$

$$\mathcal{S}_{\phi K_S} = -0.96 \pm 0.50^{+0.09}_{-0.11}, \quad \mathcal{A}_{\phi K_S} = -0.15 \pm 0.29 \pm 0.07. \quad (\text{Belle, 152M}) \quad (32)$$

While $\eta' K_S$ mode moved down by 1σ , $\mathcal{S}_{\phi K_S}$ became ~ -1 with 3.5σ significance. But the sign was no longer supported by BaBar, which reported with 114M,⁴²

$$\mathcal{S}_{\phi K} = +0.47 \pm 0.34^{+0.08}_{-0.06}, \quad \mathcal{C}_{\phi K} = +0.01 \pm 0.33 \pm 0.10. \quad (\text{BaBar, 114M}) \quad (33)$$

Although the data increase is only 30% or so, the move from Eq. (29) is more than 1σ because the earlier dataset was reprocessed, and ϕK_L events are also incorporated. Once again one has disagreement between Belle and BaBar, but the 2002 result and the 3.5σ hint for potential NP from Belle in 2003 stimulated many theory papers, mostly SUSY models with down squark flavor violation, or R -parity violation.

The latest episode is no less dramatic. At ICHEP 2004, BaBar gave^{43,44}

$$\mathcal{S}_{\eta' K_S} = +0.30 \pm 0.14 \pm 0.02, \quad \mathcal{C}_{\eta' K_S} = -0.21 \pm 0.10 \pm 0.02, \quad (\text{BaBar, 232M}) \quad (34)$$

$$\mathcal{S}_{\phi K} = +0.50 \pm 0.25^{+0.07}_{-0.04}, \quad \mathcal{C}_{\phi K} = 0.00 \pm 0.23 \pm 0.05, \quad (\text{BaBar, 227M}) \quad (35)$$

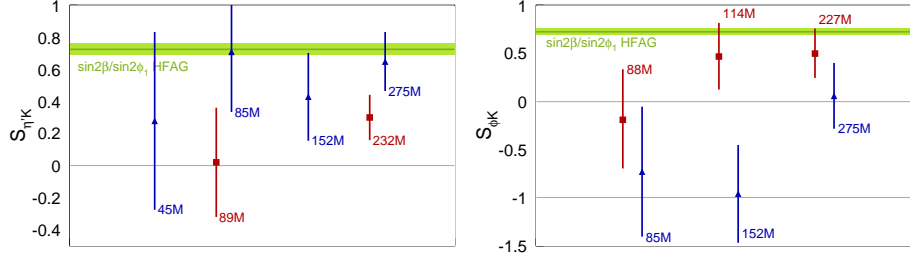


Fig. 4. Measurements of $\mathcal{S}_{\eta'K_S}$ and $\mathcal{S}_{\phi K_S}$. Square (triangle) is for BaBar (Belle).

while Belle gave⁴⁵

$$\mathcal{S}_{\eta'K_S} = +0.65 \pm 0.18 \pm 0.04, \mathcal{A}_{\eta'K_S} = -0.19 \pm 0.11 \pm 0.05, \text{ (Belle, 275M)} \quad (36)$$

$$\mathcal{S}_{\phi K} = +0.06 \pm 0.33 \pm 0.09, \mathcal{A}_{\phi K} = +0.08 \pm 0.22 \pm 0.09. \text{ (Belle, 275M)} \quad (37)$$

Except for $\mathcal{A}_{\phi K} \sim 0$, all three other measurements are not in good agreement!

The Belle value for $\mathcal{S}_{\phi K}$ changed by 2.2σ , shifting from ~ -1 in Eq. (32), to ~ 0 in Eq. (37). What happened was that the 123M new data added in 2004 gave results with sign opposite to the earlier 152M data. The new data was taken with the upgraded SVD2 silicon detector, which was installed in summer 2003. However, the SVD2 resolution was studied with B lifetime and mixing and is well understood, while $\sin 2\phi_1$ measured in $J/\psi K_{S/L}$ mode has good consistency between SVD2 and SVD1. Many other systematics checks were also done. By Monte Carlo study of pseudo-experiments, Belle concluded that there is 4.1% probability for the 2.2σ shift. Although the value is still 2σ below 0.726 (Eq. (12)), given the large shift and the poor agreement with the result from BaBar, which has been more stable (though shifted 2002 \rightarrow 2003 as commented earlier), one cannot conclude whether there is signal for NP in ϕK^0 mode.

For the $\eta'K_S$ mode, the indications from Belle and BaBar are reversed compared to ϕK_S . The $\mathcal{S}_{\eta'K_S}$ value from BaBar is 3σ below 0.726, but the result from Belle is in good agreement with SM expectations. Note also that, although the individual values for $\mathcal{C}_{\eta'K_S}$ and $\mathcal{A}_{\eta'K_S}$ are not yet significant, they are again of opposite sign and are at variance. We conclude that one has to wait further to see whether there is deviation from SM in TCPV in the $B^0 \rightarrow \phi K^0$ and $\eta'K_S$ modes. The results for $\mathcal{S}_{\eta'K_S}$ and $\mathcal{S}_{\phi K_S}$ in Eqs. (26)–(37) are plotted in Fig. 4.

4.2. Other Modes and Combined $b \rightarrow s$ Measurements

A host of other penguin dominant $b \rightarrow s$ modes have also been studied. The first such study³⁸ is $B^0 \rightarrow K^+ K^- K_S$ (excluding ϕK_S) by Belle, which has a large rate and was found to be predominantly CP even. By now one has measurements¹⁷ in $K^+ K^- K_S$, $K_S K_S K_S$ (CP eigenstate by angular momentum), $f_0(980) K_S$, $K_S \pi^0$, and ωK_S modes. The latter is studied by Belle only, disagreement exist in $K_S K_S K_S$

and $f_0(980)K_S$ modes, but the effective $\sin 2\phi_1 / \sin 2\beta$ value in $K^+K^-K_S$ and $K_S\pi^0$ modes are 1σ or more below 0.726. Although the scatter among modes differ, the effective $\sin 2\phi_1$ measured in $b \rightarrow s$ penguins measured by Belle and BaBar are both significantly below the charmonium result. The B factory average is¹⁷

$$\sin 2\phi_1(b \rightarrow s\bar{q}q) = 0.41 \pm 0.07, \quad (38)$$

which is 3.8σ below $\sin 2\phi_1(b \rightarrow s\bar{c}c) = 0.726 \pm 0.037$. There seems to be some real effect in penguin dominant $b \rightarrow s$ modes.

Besides the conflicts between Eqs. (34), (35) and Eqs. (36), (37), we remark that there are limitations for what one can interpret from deviations in penguin dominant $b \rightarrow s$ hadronic modes. While a large, definite effect in a single mode such as ϕK_S would clearly indicate NP, these modes suffer from large hadronic uncertainties, such that the NP effect would vary from mode to mode. So, whether ϕK_S or $\eta' K_S$, or the combined effect in $b \rightarrow s\bar{q}q$, one does not gain much more information by accumulating modes. It is difficult to extract fundamental information of the underlying NP. What may be more useful in the long run is $B^0 \rightarrow K_S\pi^0\gamma$ decay.

The left-handedness of weak interactions imply $\bar{B}^0 \rightarrow K^*\gamma_L$, where γ_L is a left-helicity photon; the γ_R component is suppressed by m_s/m_b in amplitude. This implies that, for $K^{*0} \rightarrow K_S\pi^0$, TCPV in $\bar{B}^0 \rightarrow K_S\pi^0\gamma$ CP eigenstate is suppressed by m_s/m_b hence close to zero, because one needs the interference between \bar{B}^0 and $B^0 \rightarrow K_S\pi^0\gamma$ amplitudes with same photon helicity, but one of which is always suppressed in SM. This is therefore⁴⁶ an excellent probe of NP that generates the “wrong” helicity amplitude, whether the NP involves new CPV phases or not. This program seemed difficult because of poor vertex resolution for the $K_S\pi^0\gamma$ final state. But in summer 2003, BaBar showed⁴⁷ that TCPV could be measured in the aforementioned $K_S\pi^0$ mode, utilizing a unique feature for the B factories, viz. that the B direction is very close to the high energy beam (e^- at present) direction. This “ K_S vertexing” technique can be applied to $K_S\pi^0\gamma$, and has now been pursued by both BaBar and Belle. The beauty of studying TCPV in $B^0 \rightarrow K^{*0}(K_S\pi^0)\gamma$ mode is that hadronic effects are largely in the $B \rightarrow K^*$ form factor, which cancels in the TCPV measurement. Thus, TCPV in $B^0 \rightarrow K^{*0}(K_S\pi^0)\gamma$ mode provides a fundamental measure of possible NP at a future high luminosity B factory.

5. The Quest for ϕ_3/γ in $B^\pm \rightarrow D^0 K^\pm$ Decay

The measurement of ϕ_3/γ is known to be difficult. We have now over 10^9 B s, but we still have not extracted ϕ_3 convincingly with the so-called DK method.

The idea of the DK method is that $B^+ \rightarrow DK^+$ decay can proceed via two paths: $B^+ \rightarrow \bar{D}^0 K^+$ via $\bar{b} \rightarrow \bar{c}u\bar{s}$, and $B^+ \rightarrow D^0 K^+$ via $\bar{b} \rightarrow \bar{u}c\bar{s}$. While the former is Cabibbo suppressed and proportional to $V_{cb}^*V_{us} \simeq A\lambda^3$, the latter is both doubly Cabibbo suppressed and color suppressed, and proportional to $V_{ub}^*V_{cs} \simeq A\lambda^3(\rho+i\eta)$. If D^0 and \bar{D}^0 decay to a common final state, the two amplitudes can interfere and probe the relative CPV phase ϕ_3 between $V_{ub}^*V_{cs}$ and $V_{cb}^*V_{us}$. The trouble is

that one has to measure very small branching ratios, controlled by the product $r_B = |V_{ub}^* V_{cs} / V_{cb}^* V_{us}| F_{cs}$, where F_{cs} is the poorly known color suppression factor.

In the so-called GLW (or $D_{CP}K$) method,⁴⁸ one studies \bar{D}^0/D^0 decay to a CP eigenstate, such as $\pi^+\pi^-$. The interference effect is between a large and a small amplitude, hence the effect is also small. In the so-called ADS method,⁴⁹ one studies \bar{D}^0/D^0 decay to a flavor specific final state such as $K^-\pi^+$. In this way, one brings down the $b \rightarrow c$ amplitude by selecting Cabibbo suppressed $\bar{D}^0 \rightarrow K^-\pi^+$ decay, thereby enhancing the interference effect. Both methods have been studied by Belle and BaBar, but so far they amount to limits on r_B and are not yet fruitful.

One interesting method was developed^{50,51} recently involving three-body decays common to \bar{D}^0 and D^0 , such as $K_S\pi^+\pi^-$. Since this method uses information from the Dalitz plot (including resonance phases), it is called the DK Dalitz plot analysis. Denote the $\bar{D}^0 \rightarrow K_S\pi^+\pi^-$ amplitude as $f(m_+^2, m_-^2)$, where $m_\pm^2 = m_{K_S\pi^\pm}^2$ are the Dalitz variables. The corresponding amplitude for $D^0 \rightarrow K_S\pi^+\pi^-$ is therefore $f(m_-^2, m_+^2)$. Thus, for $B^\pm \rightarrow (K_S\pi^+\pi^-)_D K^\pm$ decay, the amplitude is

$$f(m_\pm^2, m_\mp^2) + r_B e^{i\delta \pm \phi_3} f(m_\mp^2, m_\pm^2), \quad (39)$$

where δ is the relative strong phase between the $b \rightarrow c$ and $b \rightarrow u$ amplitudes. Belle made the first study by modelling $f(m_+^2, m_-^2)$ with known resonances, which was followed by BaBar. The extracted results are^{50,52}

$$\phi_3 = (77_{-19}^{+17} \pm 13 \pm 11)^\circ, \quad (\text{Belle, 152M}) \quad (40)$$

$$\gamma = (70 \pm 26 \pm 10 \pm 10)^\circ, \quad (\text{BaBar, 227M}) \quad (41)$$

where the last error is from $f(m_+^2, m_-^2)$ modelling. Although the ϕ_3/γ values are consistent, Belle finds a larger r_B than BaBar, which is partially reflected in the statistical error. Belle has updated with 275M $B\bar{B}$ pairs, finding⁵³

$$\phi_3 = (68_{-15}^{+14} \pm 13 \pm 11)^\circ. \quad (\text{Belle, 275M}) \quad (42)$$

These results are consistent with CKM fit results.¹⁸ Note that, with a much larger dataset, the model dependence can be removed by using a binned fit⁵¹ over the Dalitz plot.

6. Direct CP Violation in $B^0 \rightarrow K^+\pi^-$

Search for DCPV in B system is important, since a variant of the superweak model could be operative. It is remarkable that DCPV in $B^0 \rightarrow K^+\pi^-$ was observed already in 2004, just 3 years after observation of mixing-dependent CPV.

Unlike mixing-dependent CPV where one needs decay time information and tagging, the experimental study of DCPV is much simpler. They are just counting experiments, and in the self-tagging modes such as $K^\mp\pi^\pm$, one simply counts the difference between the number of events in $K^-\pi^+$ vs. $K^+\pi^-$.

Indications for a negative DCPV in $B^0 \rightarrow K^+\pi^-$ mode, defined as

$$\mathcal{A}_{K\pi} \equiv \frac{\Gamma(\overline{B}^0 \rightarrow K^-\pi^+) - \Gamma(B^0 \rightarrow K^+\pi^-)}{\Gamma(\overline{B}^0 \rightarrow K^-\pi^+) + \Gamma(B^0 \rightarrow K^+\pi^-)}, \quad (43)$$

(basically the same definition as in Eq. (6)) have been around for a couple of years. BaBar announced a value⁷ with 4.2σ significance just before ICHEP 2004, followed by Belle measurement⁸ with 3.9σ significance. The results are,

$$\mathcal{A}_{K\pi} = -0.133 \pm 0.030 \pm 0.009, \quad (\text{BaBar, 227M}) \quad (44)$$

$$\mathcal{A}_{K\pi} = -0.101 \pm 0.025 \pm 0.005, \quad (\text{Belle, 275M}) \quad (45)$$

combining to -0.114 ± 0.020 with 5.7σ significance. This establishes DCPV in B system. The QCD factorization approach predicted the opposite sign,⁵⁴ while the PQCD factorization approach⁵⁵ predicted the correct sign and magnitude. Thus, the measurement has implications for the theory of hadronic B decays.

A tantalizing hint for new physics was uncovered by Belle,⁸ and supported⁵⁶ by BaBar. By isospin one expects $\mathcal{A}_{K\pi}$ in the $K^\mp\pi^\mp$ mode and $\mathcal{A}_{K\pi^0}$ in the $K^\mp\pi^0$ mode to be very similar. However, Belle and BaBar find

$$\mathcal{A}_{K\pi^0} = +0.04 \pm 0.05 \pm 0.02, \quad (\text{Belle, 275M}) \quad (46)$$

$$\mathcal{A}_{K\pi^0} = +0.06 \pm 0.06 \pm 0.01, \quad (\text{BaBar, 227M}) \quad (47)$$

combining to $\mathcal{A}_{K\pi^0} = 0.049 \pm 0.040$, which deviates from $\mathcal{A}_{K\pi} = -0.114 \pm 0.020$ by 3.6σ . If this result persists, it would imply NP in electroweak penguins (mediated by Z^0 boson), which break isospin. However, the previous BaBar measurement⁵⁷ with 88M $B\overline{B}$ mesons gave $\mathcal{A}_{K\pi^0} = -0.09 \pm 0.09 \pm 0.01$. While consistent with zero, the sign is opposite Eq. (47). Note further that, for $K^0\pi^\mp$ mode, we have^{58,59}

$$\mathcal{A}_{K^0\pi} = +0.05 \pm 0.05 \pm 0.01, \quad (\text{Belle, 152M}) \quad (48)$$

$$\mathcal{A}_{K^0\pi} = -0.087 \pm 0.046 \pm 0.010. \quad (\text{BaBar, 227M}) \quad (49)$$

Though averaging¹⁷ to -0.02 ± 0.04 , Belle and BaBar do not agree in sign. Thus, it is not yet clear whether $\mathcal{A}_{K\pi^0}$ and $\mathcal{A}_{K^0\pi}$ have settled, although the $\mathcal{A}_{K\pi} - \mathcal{A}_{K\pi^0}$ deviation should certainly be watched closely in the near future.

7. Discussion and Prospects

We have left out many other highlights from the B factories, such as the $B \rightarrow \phi K^*$ polarization puzzle, observation of $B \rightarrow K^{(*)}\ell^+\ell^-$ and $X_s\ell^+\ell^-$, new hadron states, etc. We chose to focus on significant CPV results from the B factories.

It is clear that TCPV in $b \rightarrow s(\overline{c}c)_{\text{charmonium}}$ modes are now firmly established, with good agreement between Belle and BaBar. What is surprising is that, while Belle and BaBar have each made impressive TCPV measurements in $\pi^+\pi^-$, ϕK_S and $\eta'K_S$ modes, agreement has not been reached in any of these modes! Just compare Figs. 3 and 4 with Fig. 2. The statistics may be still insufficient, and

perhaps some algorithmic improvements need to be made, since the charmless modes are not background free.

We expect the $\pi^+\pi^-$ study to converge in a year or two, but an isospin analysis may need a couple more years for $\pi^0\pi^0$ measurement to become more precise. Alternatively, if Belle completes the $\rho\rho$ and/or $\rho\pi$ studies and concur with the BaBar findings, then the B factories could claim the measurement of α/ϕ_2 in a year or so. However, at this point one cannot rule out further conflicts to develop.

The current 3.8σ deviation between $\sin 2\phi_1$ measured from penguin $b \rightarrow s$ modes vs. $b \rightarrow s(\bar{c}c)_{\text{charmonium}}$ is significant, and possibly hints at New Physics. But Belle and BaBar disagree on the key ϕK_S and $\eta' K_S$ modes. These two modes (as well as the higher statistics $K^+K^-K_S$ mode) may take several years to clear up as one needs a few times more data. Other modes would have to wait even longer, and modes like $K_S\pi^0\gamma$ would probably have to await the Super B factory with an order of magnitude or more increase in luminosity.

The ϕ_3/γ measurement using DK Dalitz analysis looks promising. In a few years it would become systematics limited, and at the Super B factory one can use the model independent binned fitting approach.

Direct CPV has been established in $B^0 \rightarrow K^+\pi^-$ mode. We expect a few more measurements to appear in next few years, such as in $\pi^+\pi^-$, $\rho^\pm\pi^\mp$, and maybe $K^+\pi^0$, $K^0\pi^+$ and $\eta K^+/\pi^+$. If the $\mathcal{A}_{K\pi} - \mathcal{A}_{K\pi^0}$ difference persists, which may be known within a year, then we may have New Physics in electroweak penguins.

We conclude that, before LHC starts to produce physics, we expect α/ϕ_2 and ϕ_3/γ to be measured, and CKM unitarity can be checked by direct measurement to some accuracy. If New Physics effect is at the 20% level or more for TCPV in penguin $b \rightarrow s$ modes, it would be discovered. However, we may know in a year or two whether we have New Physics in the electroweak penguin.

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16 *W.S. Hou*

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